Frequency Hopped CDMA for Third Generation Mobile Radio Systems

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Abstract

Third Generation Mobile Radio Systems are currently being proposed that will provide unified mobile access to a wide range of services for the mass user market. Code Division Multiple Access (CDMA) is now recognised by many as one of the most viable access techniques to provide the flexible air interface required. In this contribution, Frequency Hopped (FH) CDMA is investigated, and a system architecture is proposed to rival the more widely researched Direct Sequence (DS) approach. The results presented here concur with other recent work in finding that the claimed advantages of DS can also apply to Frequency Hopping.

1 Introduction

Future Personal Communication Systems (PCS) will provide a universal system solution to the problem of satisfying the mass-user market demand for a wide variety of services operating in a wide variety of propagation environments. These services will vary from basic voice and low rate data (< 9.6kbps), through medium rate data and 64 kbps video telephony, up to a possible limit of 2 Mbps for high rate data transmission. Such services must be offered using low-cost, power efficient user terminals, providing high quality of service with a high system capacity if the goals of PCS are to be met. Whilst the implementation of such a complex system is a decade away, consideration of the necessary flexible air interface is required now. Current system proposals include the CCITT Future Public Land Mobile Telecommunications System (FLPMTS) and the European Mobile Telecommunications System (UMTS) [1]. Extensive research is currently underway into the most suitable access methods; the two most favoured appearing to be Time Division Multiple Access (TDMA) and CDMA. Under the European RACEII research programme, CODIT is developing a code-division test bed, using DS technology, whilst the ATDMA project is researching advanced TDMA techniques. A comparison of both the main CDMA techniques, Direct Sequence (DS) and Frequency Hopping (FH) has been undertaken by the UK SERC/DTI LINK project "A Rigourous Evaluation of CDMA Techniques for Future European Personal Communication Systems". The anticipated levels of complexity and performance of each approach have been compared and contrasted for the many requirements of the third generation systems. Some of the findings of this work are given in [2].

The hardware considerations for a frequency hopping system have been evaluated by Busby [3]. For slow hopping, with several transmitted data symbols per hop, corresponding to hop rates of around 1000 hops per second, it is suggested that a relatively simple, inexpensive, low power single loop frequency synthesiser may be utilised. Furthermore, recent innovations in digital up/downconverters allows use of a hopped IF oscillator, providing the possibility of combined IF/baseband synchronisation and tracking functions. The various solutions proposed for the required hardware FH subsystems are expected to be no worse, in terms of size, cost and *overall* power drain than for the presently trialled DS systems.

Thus, it would seem that some of the traditional shortcomings of Frequency Hopping can now be discounted. Recent research [4, 5, 6] has proposed slow FH as a viable contender for third generation systems. In this paper, a slow frequency hopping architecture is presented, in which various parameters have been considered. The operation of both QPSK and a high level linear modulation scheme (16APSK) have been simulated, utilising a variety of coding strategies. In addition, propagation measurements taken by the authors have been used to validate the software fading model employed. A multiuser scenario has been encompassed into the simulations, and results are presented for the capacity expected.

2 System Architecture

Slow Frequency Hopping does not benefit from the frequency diversity associated with transmitting the same symbol on multiple frequencies (Fast Frequency Hopping). However, by reducing the hop rate, as already discussed, practical hopping synthesisers can be more readily implemented. Furthermore, the requirements upon the tracking and synchronisation subsystems are greatly relaxed at, for example, 1000 hops per second, compared to achieving chip synchronisation in a DS system, chipping at rates of several Mchips per second.

The major benefit of slow hopping is the possibility to have all users within a cell hopping synchronously. Every user within the cell operates with a *different* phase offset of the *same* hopping code. The synchronised hopping ensures that no user clashes, on any hop, with the frequency bins of any other, within the user's cell. Completely removing the intra-cell interference greatly improves performance. Path loss and shadowing reduces the effects of other clashing users in the surrounding cells, and since they are un-synchronised, with a different hop pattern, no one interferer has any significant effect for any prolonged period. *Interference diversity* may be considered as the beneficial effect of spreading the interference caused by such clashing users, over several hops-worth of data through the use of interleaving. Complete frequency re-use becomes possible, negating the need for complex frequency planning and management. Frequency re-use over a cluster of cells, as in the traditional FDMA approach, is replaced by code re-use, where each cell within a certain sized group has a different hopping sequence, to ensure minimum interference.

The use of a highly bandwidth efficient linear modulation scheme, known as 16APSK , has been considered as suitable for frequency hopping [7]. Initial simulations of the single user link showed considerable promise but when compared to a lower level modulation, such as $\pi/4$ QPSK, 16APSK suffers a large E_b/N_0 penalty. This translates to a considerably lower C/I tolerance for APSK, compared to QPSK, in the multi-user environment. The performance of hopped 16APSK against $\pi/4$ QPSK is shown in Figure 1. Both are operated differentially, in order that the non-linearites of the FH channel can be overcome, and rapid response is possible at the receiver, so that the short dwell time can be handled. The irreducible error can be overcome through use of antenna diversity. With differential operation, the phase decoding becomes implicitly maximal ratio, whilst the amplitude decoding for the 16APSK entails equal gain combining [8].

In the multi-user scenario, the use of FEC coding, in

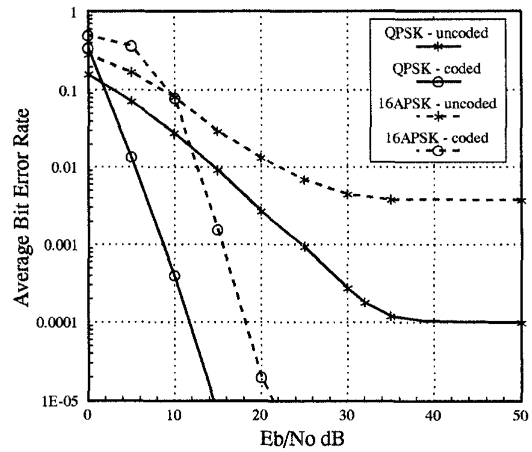

Figure 1: Performance of hopped 16DAPSK against $\pi/4$ DQPSK (500 hops per second)

addition to block interleaving, is a necessity in order to overcome high outages occurring during frequency bin clashes.

There is clearly a trade-off between increasing the number of FH bins in a given frequency allocation, which increases the system processing gain and hence reduces interference, and the fundamental immunity to interference of the modulation format itself.

3 System Simulation

The model developed for 16APSK hopped operation is fully described in [7]. The narrowband modulated message signal is actually transmitted through a frequency hopping channel model, avoiding the need for simulation of a frequency hopper, a fixed wideband channel model and a de-hopper. The narrowband hopping channel model generates different fading envelopes from hop frame to hop frame. Recent propagation measurements [9] have confirmed its behaviour as realistic of the FH channel. Whilst the long term statistics of the received signal are not significantly altered by hopping, various short term statistics, such as the fade rate and duration are dependent upon hop rate. A reduction in the duration of deep fades is advantageous, in that the length of error bursts arising in such fades is reduced. This relaxes the requirements upon the receiver, in terms of the interleaving depth and coding complexity necessary to meet a specified level of performance. Given that the performance of the channel model has been verified, the effects of varying hop rate can be investigated. Several coding schemes have been considered, including a (15,7)

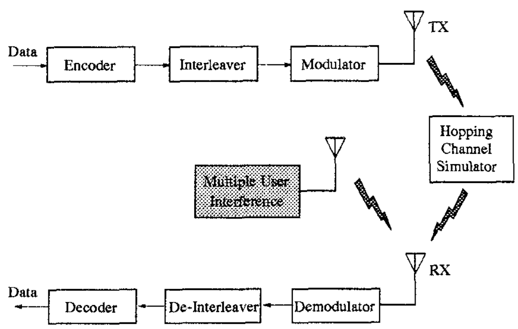

Figure 2: Schematic of FH-CDMA Multi-User Simulation

BCH code, and a 1/2 rate,constraint length 7, convolutional code. The coded performance of the modulation schemes under consideration, with the 1/2 rate convolutional code, are shown in Figure 1.

Whilst the effects of other users, within the wanted user's cell, are ignored by assuming fully synchronised cyclical hopping, out-of-cell interference must be considered. A network topology may be specified, taking account of parameters such as voice activity, cell loading and the required propagation environment. A reference file of interference data is generated using a statistical distribution of other users. This is summed with the wanted hopped signal, as additive interference, as indicated in the schematic of Figure 2. For the basic voice FH-CDMA system, an outage threshold of 10^{-3} BER has been defined. This is applied over a period of 10^4 information bits, and repeated to generate the required outage statistics.

The following information summarises the system parameters used for the simulations presented here:

- Network Topology
  37 Base Stations in hexagonal cellular geometry,
- Propagation Environment
  Log-normal Shadowing (σ = 8dB), Fast Fading $f_d T_s$=0.01,
- Power Control
  Assumed to be ideal, overcoming the slow varying propagation effects of path loss and shadowing.

No cell sectorisation has been applied. As already described, full frequency re-use is assumed within each cell, with synchronous hopping. Both 16APSK and $\pi/4$ QPSK modulations have been used, with a hop rate of 1000 hops per second. A basic information bit rate of 10 kbps, comprising 8 kbps voice data and 2kbps control data, has been used, with Root Raised Cosine filtering (α =0.6) at both the transmitter and receiver. The simualted hopping bandwidth is 1MHz, giving 125 and 62 available hop channels, for 16APSK and QPSK respectively.

4 Results

A comparison of the performance of 16APSK and QPSK is shown in Figure 3. Taking 1% of users in outage as an acceptable system performance criterion, approximately 29 users/MHz/cell can be supported by QPSK, whilst 22 users/MHz/cell is offered by 16APSK.

The variation in performance with coding scheme is illustrated by Figure 4. This shows QPSK at 1000 hps operating with both the 1/2 rate convolutional code copared to the (15,7) BCH code. The convolutional code is seen to have superior performance, since the BCH code only offers 18 users/MHz/cell.

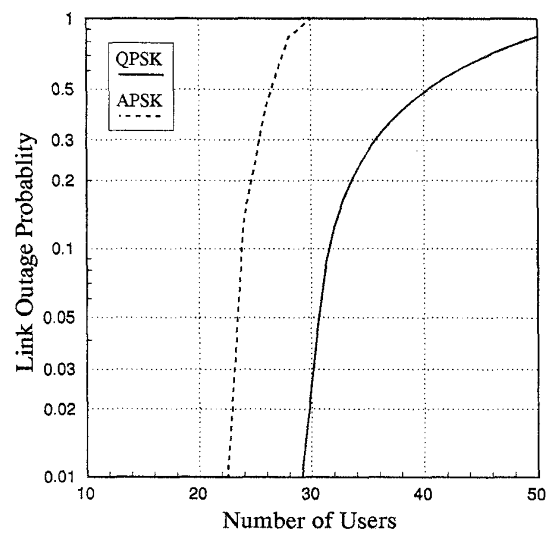

Figure 3: Link Outage Probabilities for QPSK and 16APSK

5 Discussion

From Figure 3, it is obvious that 16APSK has a far lower tolerance to interference. This modulation format is twice as bandwith efficient as QPSK, thereby offering twice as many hop channels/MHz. Despite lowering the

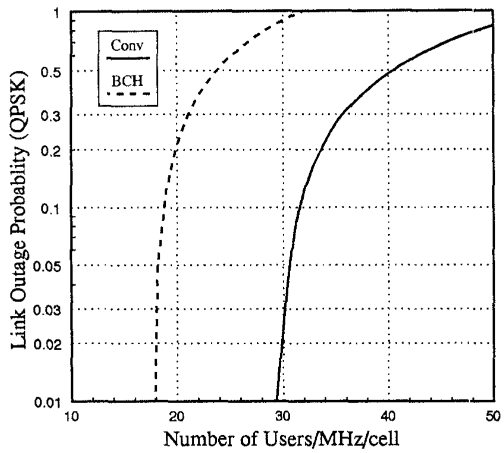

Figure 4: Coded Link Outage Probabilities

average level of interference on any particular hop, its immunity to that interference is very low. 16APSK is a high level modulation, with 8 phase symbols and 2 amplitude rings, and is thereby susceptible to distortion of the received symbol vector by an interfering signal.

The nature of the errors introduced by the multi-user interference channel is non-deterministic. The combined signals of interfering users from all other cells, on top of the faded wanted signal is such that error bursts appear, genarally over a fraction of the hop. The use of de-interleaving increases the separation of the erroneous bits from such bursts, thereby randomising the errors and allowing their removal by the decoder. However, if the number of hits is too large, errors from different hops are actually de-interleaved closer together. A large number of closely spaced errors inevitably leads to breakdown of the convolutional code. This occurs when too many errors appear within the truncation depth of the decoder, and results in error bursts appearing in the decoded bitstream. The same phenomenon is observed with the BCH code, however, this has a lower overall performance than the convolutional code, as seen in Figure 4.

Although not conclusive, this study has clearly demonstrated that the performance of a FH-CDMA cellular system, in terms of capacity, is equivalent to, or better than comparable DS-based systems.

Future work will include the further optimisation of the proposed FH-CDMA architecture, in terms of the choice of coding and the selection of hopping parameters. The sensitivity of FH to system imperfections, such as errors in the power control mechanism will also be pursued.

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